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Precise orbit determination and rapid orbit recovery supported by time synchronization

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Abstract

In order to maintain optimal signal coverage, GNSS satellites have to experience orbital maneuvers. For China's COMPASS system, precise orbit determination (POD) as well as rapid orbit recovery after maneuvers contribute to the overall Positioning, Navigation and Timing (PNT) service performance in terms of accuracy and availability. However, strong statistical correlations between clock offsets and the radial component of a satellite's positions require long data arcs for POD to converge. We propose here a new strategy which relies on time synchronization between ground tracking stations and in-orbit satellites. By fixing satellite clock offsets measured by the satellite station two-way synchronization (SSTS) systems and receiver clock offsets, POD and orbital recovery performance can be improved significantly. Using the Satellite Laser Ranging (SLR) as orbital accuracy evaluation, we find the 4-hr recovered orbit achieves about 0.71 m residual root mean square (RMS) error of fit SLR data, the recovery time is improved from 24-hr to 4-hr compared with the conventional POD without time synchronization support. In addition, SLR evaluation shows that for 1-hr prediction, about 1.47 m accuracy is achieved with the new proposed POD strategy.

Keywords: Time synchronization; Precise orbit determination; Clock offset; Satellite laser ranging; User equivalent range error

1. Introduction

Broadcast ephemeris and clock parameters are updated on a regular basis, for precise positioning, navigation and timing services which requires continuous and stable satellite precise orbit determination (POD) and prediction by the ground segment. The space segment of the COMPASS satellite navigation system consists of geostationary earth orbit (GEO) satellites, inclined geosynchronous orbit (IGSO) satellites and medium earth orbit (MEO) satellites (Zhou et al., 2011, 2012; Mao et al., 2011; Lei et al., 2011). Orbit maneuvers are conducted regularly to hold orbit positions and to maintain the service area. Due to the difficulty in modeling the maneuver thrust, combined POD cannot be carried out with tracking data including both before and after the maneuver, especially for the real-time POD mode. Given the constellation characteristics of the COMPASS satellite navigation system, rapid orbit recovery capability is important to prevent the loss of satellite availability and degradation of the navigation performance (Guo et al., 2010a; Huang et al., 2008; Bennett et al., 2013).

A maneuvering satellite is usually removed from the multi-satellite precise orbit determination (MPOD), and observation data before and during the maneuver process are also usually eliminated and no longer participate in

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the POD. The tracking observation data are accumulated again starting from the end of maneuver. When the single-satellite precise orbit determination (SPOD) has become stable, the maneuvered satellite is reincorporated into the MPOD. Affected by ground tracking geometry, number of observations, data noise and error sources, the average recovery time is generally about 24 h for maneuvering satellites, before the POD accuracy reaching the normal level. Therefore the satellite is not available for a long period, and the service performance is consequently degraded (Guo et al., 2010a; Huang et al., 2008).

At present the traditional methods to improve POD accuracy include ground tracking network expansion, dynamic model refinement, observation accuracy improvement, and both station and satellite clock offsets fixing (Guo et al., 2010c). POD technique based on C-band ranging has been investigated in several references (Li et al., 2008; Huang et al., 2008), while the system error is the key to limit orbit determination and prediction accuracy. The system errors can be corrected through external independent tracking techniques (such as SLR), making the dependency on SLR data too strong (Guo et al., 2010b). Therefore further study and investigation of POD methods are desired.

Along with the expansion of the ground tracking network, observation data also increase notably, such as pseudorange, carrier phase, and clock offsets data. In this paper we propose to utilize these data comprehensively to accomplish rapid orbit recoveries for COMPASS navigation system, especially the high accuracy phase data and satellites clock offsets (Zhou et al., 2011, 2012). With this method we are able to diminish the effect of system errors on the orbital accuracy and to improve the SPOD accuracy for some individual satellites with poor tracking geometries.

We report in this paper the efforts to accomplish rapid orbit recoveries and to improve the SPOD accuracy. A new POD strategy is studied for the first time with the constraint of time synchronization. For the new strategy, satellite clock offsets are measured with the satellite station two-way synchronization (SSTS) method (Liu et al., 2004a), station clock offsets are estimated in the MPOD based on both the pseudorange data and the phase data, dynamic model parameters and system errors are restricted and optimized. The POD experiments with real pseudorange data and carrier phase data show that rapid orbit recoveries have been realized and stable and continuous SPODs are achievable for individual satellites with poor tracking geometries, leading to the notable improvement in the satellite availability and navigation performance.

2. Estimation of satellite clock offsets and station clock offsets

Estimated satellite clock offsets and station clock offsets are important by-products in the POD using L-band pseudorange and phase data collected by monitoring receivers. Two different methods of clock estimation are adopted in this paper. The first method is called the integrated solution method, with orbit elements and clock offsets being estimated simultaneously in the MPOD. The second method is called the independent solution method, for which the orbit elements are estimated in the POD, while both stations and satellites clock offsets are measured or estimated independently with two-way satellite time and frequency transfer (TWSTFT) data to eliminate error sources such as orbit error, receiver coordinates error and propagation errors (Li et al., 2008).

2.1. Clock offsets estimation with MPOD

In the MPOD process, the clock offsets will either be eliminated by double-differencing, or can be estimated for each epoch based on the pseudorange and phase data without differencing. The zero-differencing method is introduced below in this section.

The pseudorange and carrier phase ionospheric free combinations are usually adopted in the MPOD. Details of the observation model can be found in several references (e.g., Mao et al. (2011), Zhou et al. (2011)).

Estimating all satellite and all station clock errors for each epoch increases the normal equation size and decreases the processing efficiency. We adopt a clock error elimination algorithm which effectively separates clock error estimates from orbital and other non-random parameters to save computation resources. In the procedure, clock offsets are eliminated epoch by epoch with a fixed reference clock. Only global parameters are kept in the final normal equation, such as satellite orbit elements, phase ambiguities and other dynamic parameters (Zhou et al., 2011).

The estimated satellite clock offsets are correlated with the orbital elements in the MPOD process. Therefore the estimated satellite clock offsets show correlations with the orbit radial error, and might not reflect the clock physical characteristics. But for station clock offsets estimated in MPOD, one station can track all visible satellites, with one common station clock offset. With increasing number of satellites in a GNSS constellation, it becomes more convenient to separate the station clock from the satellite clock.

Experiments with real COMPASS satellite clock offsets data show that the linear fitting error is about 2.1 ns (RMS) for 2-hr clock offsets time series, and about 0.7 ns for station clock offsets. And closure errors are close to zero among three station clock offsets. The closure error is defined as follow:

$$\Delta = \tau_{12} - \tau_{13} + \tau_{23} \tag{1}$$

where, τ_{12} is the clock offset of station-1 referred to station-2, τ_{13} is station-1 referred to station-3, and τ_{23} is station-2 referred to station-3.

Thanks to the carrier phase data in the integrated-solution method, precise clock offsets are estimated in the